IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

STOCHASTIC COOLING IN THE CERN ISR DURING $p\bar{p}$ COLLIDING BEAM PHYSICS

E. Peschardt and M. Studer
CERN, 1211 Geneva 23, Switzerland

Introduction and Summary

When the ISR is used as a $p\bar{p}$ collider a high-intensity proton beam in R1 collides with a low-intensity antiproton beam in R2 for periods of up to two weeks. The luminosity lifetime is increased with a vertical stochastic cooling system in R1 designed for currents up to 10 A with a total bandwidth of 3.3 GHz. Cooling rates up to 0.7%/h have been obtained. The R2 antiprotons are cooled vertically with a 100-600 MHz system which decreases the initial beam height by up to a factor 7 and increases the luminosity by a factor 1.3-1.4. A momentum cooling system in R2 (frequency range: 55-155 MHz) creates empty space within the $\bar{p}$ stacking aperture. This allows several stacks from the antiproton accumulator (AA) to be stored in the ISR. With this system which uses the Palmer method[1] it has been proved experimentally that momentum cooling and horizontal betatron cooling are obtained simultaneously if the betatron phase between pick-up and exciter is an odd number of half-betatron wavelengths. The cooling rate of the momentum cooling system which is power-limited is typically 4%/h at 26 GeV/c.

The layout of the cooling systems is shown schematically in Fig. 1. The position of the various elements is mainly determined by the available free space and the lattice parameters.

Future applications include vertical cooling of α-particles and cooling of antiprotons in all three planes in an experiment where a circulating 3.5-7.5 GeV/c $\bar{p}$ beam collides with a hydrogen gas jet target.

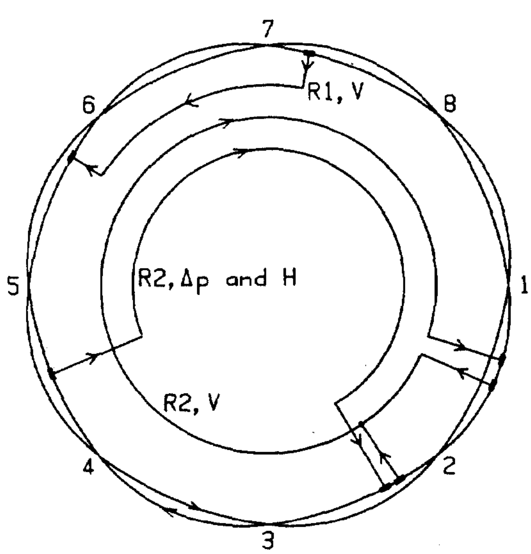

Fig. 1. The cooling systems in the ISR. All the components for the R1 system are in the tunnel. The R2 systems are designed with long delays. This makes it possible to install major parts of the systems in auxiliary buildings.

The Vertical Betatron Cooling system in R1

With the slot-type pick-up and kicker developed by L. Faltin[2] a broadband cooling system has been constructed for vertical cooling of medium intensity beams. Both devices are divided into identical halves for treating the inner and outer parts of the beam separately. They are usable up to 4 GHz but with the chosen slot size (4 × 30 mm) the upper 3 dB cut-off frequency is 3 GHz. With all the system components included, the measured 6 dB cut-off frequencies were 0.85 and 2.5 GHz giving a total bandwidth of 3.3 GHz for beams large enough in momentum to be seen by both system halves. The kicker is driven by two 1-3 GHz, 0.5 W solid state amplifier. The power is sufficient for optimum cooling of stacks larger than 5 A. The maximum phase error is 20° with phase equalizers included.

The cooling rates for the system were estimated using the formula[3]

$$\frac{1}{\tau} = \frac{W}{2N}\left[2g - g^2(M + U)\right]$$

where W is the bandwidth, N the number of particles, g the system gain taken from the measured frequency response, M the mixing factor and U the noise-to-signal power ratio.

With overlapping transverse and longitudinal Schottky bands the main contribution to the heating term is from the residual longitudinal Schottky signal originating from the finite common-mode rejection. Therefore the cooling rate depends strongly on the vertical beam size. Typically for a 10 A stack with a σ_V of 1.2 mm the calculated cooling rate is 0.7%/h which is about the same as the blow-up rate due to intra-beam scattering and gas scattering. For this reason it is not expected that the system will decrease the initial beam height; at best the σ_V is kept constant.

The system has been in operation for several of the $p\bar{p}$ physics periods. In one case a proton stack was kept circulating for nine and a half days. Cooling was applied during the first four days and the last 50 hours of this period. The beam height was measured regularly with a vertical transverse Schottky scan normalized with the square root of current.

The cooling rate of the system varied between 0.3%/h and 0.65%/h. Figure 2 shows the vertical Schottky scan before and after the last 50 h of cooling. A comparison between the two signals shows that the performance of the inner half system is better than for the outer half system which has a small delay error. This emphasises the problems with the setting up of the system which is only with difficulty adjusted by comparing the Schottky scans with the loop open and closed. The mixing is almost complete and the overlap between the transverse and longitudinal Schottky bands makes it difficult to measure the vertical Schottky scan from the cooling pick-up.

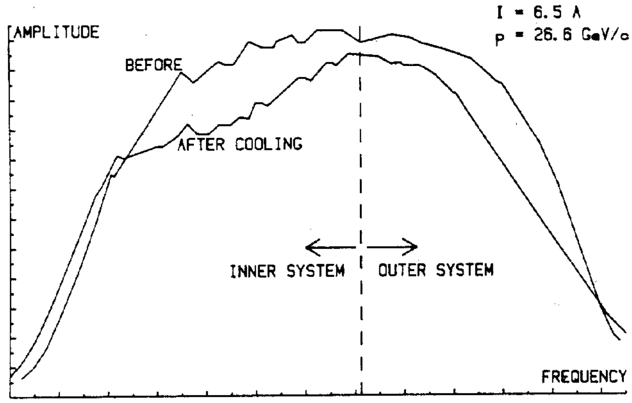

Fig. 2. Vertical Schottky scan taken at 10.7 MHz before and after a 50 h period of vertical betatron cooling.

The Vertical Betatron Cooling System in R2

The antiprotons are cooled in the vertical plane with a system based on a directional coupler pick-up and kicker. The plate length of 155 mm was chosen to be such that the system works up to frequencies where waveguide modes propagate inside the vacuum chamber[4]. The pick-up assembly is composed of two pick-ups, the signals from which are added for increased signal-to-noise ratio. With two assemblies (Fig. 1), one for a Q-value of 8.62 (FP working line) and another for a Q-value of 8.88 (ELSA or DL working line) the system can be used for all the standard ISR working conditions[5].

With carefully designed gain equalizers a 100-600 MHz frequency range could be obtained. The maximum kicker power is 2 W which is sufficient for currents in the mA range.

Run No.	Working line	Momentum (GeV/c)	Current (mA)	Beam height decrease
1256	FP	31.4	2.0	factor 1.9 in 7 h
1257	FP	31.4	3.4	factor 2.2 in 50 h
1272	FP	15.4	4.2	factor 7 in 130 h
1278A	DL	26.6	1.2	factor 3 in 27 h
1278B	DL	26.6	2.3	factor 2.2 in 19 h
1278C	DL	26.6	3.6	factor 2.3 in 63 h
1278D	DL	26.6	4.3	factor 1.4 in 15 h
1317A	DL	26.6	2.8	factor 2.2 in 65 h
1317B	DL	26.6	5.4	factor 1.4 in 15 h
1317C	DL	26.6	6.6	factor 2 in 230 h

Table I. Decrease in $\bar{p}$ beam height with vertical betatron cooling for all the periods with antiprotons in 1982.

The system has been in operation in all the periods with $p\bar{p}$ colliding beam physics (see Table I). The decrease in vertical height depends almost entirely on the initial vertical emittance of the antiproton beam. Cooling ceases when the signal-to-noise ratio has decreased to ~0.2. The final beam height is not known with precision but in one case a σ_v of about 0.4 mm in a standard intersection was measured from the scraping of a 2 mA antiproton stack. For a proton beam $\sigma_v > 1.0$ mm, hence the luminosity

$$L \propto 1/\sqrt{\sigma_1^2 + \sigma_2^2}$$

is almost entirely determined by the proton beam height and a factor 1.3-1.4 is gained with the cooling system if it is supposed that the beam height is the same for the p and $\bar{p}$ stacks if cooling is not applied.

The Momentum Cooling System

The stacking aperture in the ISR for protons is 60 mm but for antiprotons this aperture is limited to 20 mm by a detector magnet. To allow several stacks from the antiproton accumulator to be stored in the ISR it has therefore been necessary to construct a momentum cooling system for the antiprotons (see the $\bar{p}$ transfer procedure in ref. 5). The system uses the Palmer method[1] and is designed in such a way that momentum cooling and horizontal betatron cooling are obtained simultaneously. The position-dependent gain is produced by a partial aperture pick-up with minimum gain at the centre orbit (Fig. 3). In total four pick-ups are used. The correcting elements are four wideband accelerating gaps driven by four 50 W solid-state amplifiers. With a pick-up length of 694 mm the system has a bandwidth of 100 MHz with 6 dB cut-off frequencies at 55 and 155 MHz.

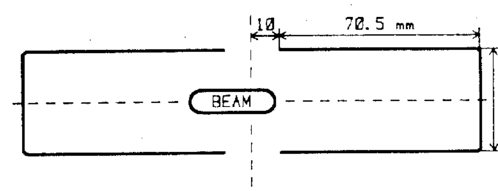

Fig. 3. Cross-sectional view of the momentum cooling pick-up.

The position to which the particles converge can be varied with a radial bump in the pick-up.

The system has been in operation in two $p\bar{p}$ physics periods. Momentum cooling is illustrated in Fig. 4. With the radial bump chosen to be such that the particles accumulate close to the outer aperture limit the stack core is not disturbed when the next AA stack is deposited at the low momentum edge. In this case a bump of 6 mm was applied and the final 6.66 mA $\bar{p}$ stack was built up from three AA stacks with momentum cooling between the transfers.

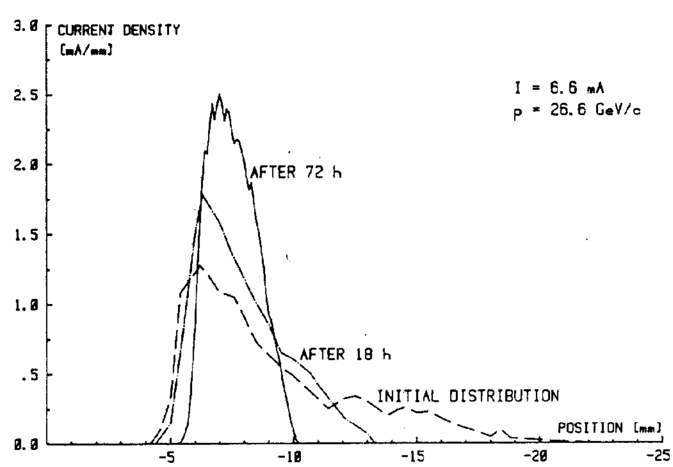

Fig. 4. Antiproton stack profile with time. In total this beam was kept circulating for more than ten days and finally a peak density of 2.8 mA/mm was reached.

The horizontal betatron cooling rates are measured using the Schottky signals produced by the cooling pick-up. From the scans shown in Fig. 5 a cooling rate of 2.8%/h was measured. The momentum cooling rate was 4.0%/h in the same period.

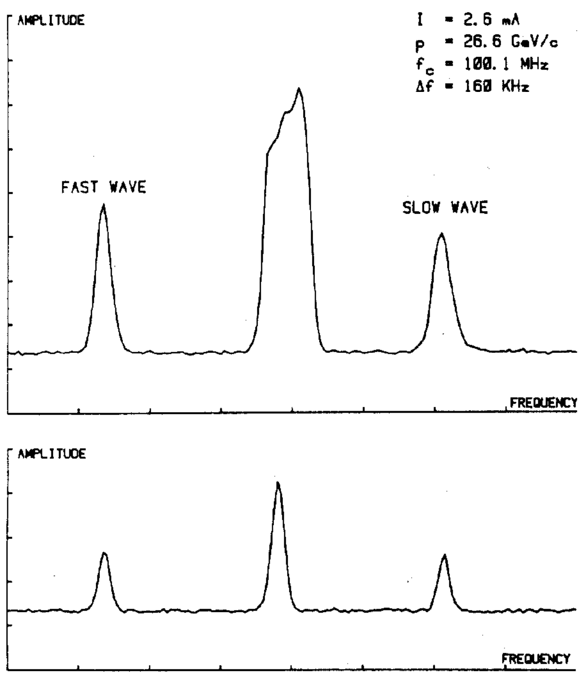

Fig. 5. Horizontal Schottky scan of an antiproton beam before and after 30 h of momentum cooling. The decrease in amplitude shows that the beam size in the horizontal plane has decreased by a factor 2.3.

The relation between the two cooling rates has been calculated by H.G. Hereward[6]. In the ISR the cooling gain is small at 26.6 GeV/c and there is no overlap between the transverse and longitudinal Schottky bands. The horizontal cooling rate $1/\tau_\beta$ is then related to the longitudinal cooling rate $1/\tau_p$ by

$$\frac{1}{\tau_\beta} = -\frac{1}{2} \cdot k \cdot \cos\theta \cdot \frac{1}{\tau_p}$$

where θ is the betatron phase advance from pick-up to kicker and k is given by

$$k = \frac{\alpha_{pk}}{\alpha_{ppu}} \sqrt{\frac{\beta_{pu}}{\beta_k}}$$

with the dispersion α_p and the betatron lattice parameter β in pick-up and kicker. For the following parameters, $\alpha_{ppu} = 2.47$, $\alpha_{pk} = 2.38$, $\beta_{pu} = 25$ m, $\beta_k = 14.4$ m and $\cos\theta = -1.00$, this gives:

$$\frac{1}{\tau_{\beta calc}} = 0.63 \cdot \frac{1}{\tau_p}$$

which can be compared with

$$\frac{1}{\tau_{\beta measured}} = 0.70 \cdot \frac{1}{\tau_{p measured}}$$

The small discrepancy is probably due to the measured τ_p which was taken from a non-symmetrical longitudinal distribution.

The Influence of the Cooling Systems on the Background Rates

All the cooling systems in the ISR are in operation in "stable beam" periods where uncontrolled beam losses complicate the data-taking by increasing the background noise seen by the detectors. In the long term the cooling systems have a beneficial effect on the background level because the systems move the beams away from the aperture limits. Initially, however, the distribution function might have sharp edges. The imaginary part of the beam transfer function is then large. This affects the cooling in such a way that the beam is locally heated and an increase in the background rate is observed if the aperture is restricted in an interaction region. In the ISR the p stacking aperture is small and the initial density distribution often irregular. In some cases the momentum cooling system caused small beam losses and a perturbing increase in the background rate.

The vertical cooling system in R2 has never negatively affected the background rate. The system in R1 has only perturbed the data-taking for an experiment which measured the pp cross-section with detectors close to the beams.

Other applications

In an experiment in preparation in the ISR a low-energy antiproton beam (3.5-7.5 GeV/c) in R2 collides with a hydrogen gas jet. In this mode of operation cooling in both the vertical and longitudinal planes is essential. The p lifetime is increased with the vertical cooling system which counteracts the rapid vertical growth caused by the gas curtain on the circulating beam. With the momentum cooling system the required high mass resolution is obtained and the momentum loss caused by the gas jet neutralized. In a test with the gas jet and protons at 4.05 GeV/c the equilibrium σ_v was 1.2 mm and the minimum rms momentum spread obtained was ±0.08% for a beam current of 6 mA.

A period of colliding beam physics with α-particles is planned for this year. The broadband vertical cooling system in R1 will then be used for cooling of α-particles. A cooling rate of 2-3%/h is expected for a 5 A stack at 26 or 31 GeV/c.

Acknowledgements

Where possible the cooling systems are constructed from hardware used for the first experiments with stochastic cooling in the ISR. The slot-type pick-up and kicker was developed by L. Faltin. The cooling gaps and the momentum cooling pick-up were constructed by G. Carron and L. Thorndahl. The authors are grateful for this assistance.

References

1. R.B. Palmer, Stochastic Cooling, BNL Report, BNL 18395, 1973.
2. L. Faltin, Slot-type Pick-up and Kicker for Stochastic Beam Cooling, Nucl. Instr. & Methods, 148 (1978), p. 449.
3. D. Möhl, G. Petrucci, L. Thorndahl, S. van der Meer, Physics and Technique of Stochastic Cooling, Phys. Rep. 58 (1980), p.73.
4. G. Carron, L. Faltin, W. Schnell and L. Thorndahl, Experiments with Stochastic Cooling in the ISR. IEEE Trans. Nucl. Sci., NS-24, No.3, p. 1402.
5. P.J. Bryant, Antiprotons in the ISR, Contribution to this Conference.
6. H.G. Hereward, in Theoretical Aspects of the Behaviour of Beams in Accelerators and Storage Rings, CERN 77-13, pp. 281-289.